
A Tomographic Technique for Aerodynamics at Transonic Speeds

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A TOMOGRAPHIC TECHNIQUE FOR AERODYNAMICS AT TRANSONIC SPEEDS

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Summary

Computer-aided tomography (CAT) provides a means of noninvasively measuring the air-density distribution around an aerodynamic model. This technique is global in that a large portion of the flow field can be measured. A test of the applicability of CAT to transonic velocities was the objective of this investigation. A hemispherical-nose cylinder afterbody model was tested at a Mach number of 0.8 with a new laser holographic interferometer at Ames Research Center's 2- by 2-Foot Transonic Wind Tunnel. Holograms of the flow field were taken and were reconstructed into interferograms. The fringe distribution (a measure of the local densities) was digitized for subsequent data reduction. A computer program based on the Fourier-transform technique was developed to convert the fringe distribution into three-dimensional densities around the model. Theoretical aerodynamic densities were calculated for evaluating and assessing the accuracy of the data obtained from the tomographic method.

INTRODUCTION

For many years, aerodynamicists have used Mach-Zehnder interferometry for both qualitative flow visualization and quantitative density measurements. However, that technique is not practical in larger wind tunnels because of its sensitivity to vibration and the expense of the very high quality optics it requires. Thus, its use has been limited to small laboratory experiments.

During the past decade laser holographic interferometry has been developed into a practical technique that possesses excellent potential for large-field, quantitative density measurements. Many research laboratories are now using laser holographic interferometry for airfoil work, turbomachinery research, jet-exhaust studies, and many other types of fluid-flow investigations [1-15]. These applications can be categorized into two-dimensional and three-dimensional flows. Two-dimensional flows would include airfoils [13,14], corner flows [15], and channel flows [16].

Holographic interferometry for two-dimensional flows has proved to be a practical measurement method, one reason being that the optical path

lengths in two-dimensional flows are usually long enough so that there are sufficient fringes for good signal resolution. In addition, an algebraic expression that relates the density to the fringe count makes the data reduction problem manageable. In fact, for the case of infinite fringe interferograms, the fringes are contours of constant density.

For the general case of three-dimensional flow, such as airplane models, rotating rotor blades, jets, and nozzles, CAT (Computer Aid Tomography) methods are being used to extract the density from the fringe data. CAT combines holographic interferometry, for taking multiple views of the flow, and a computer to solve an integral equation relating the fringe data to the density. Some initial experiments [12,17,18] indicate that the CAT methods are potentially effective means of measuring three-dimensional flows. Perry and Lee [19] tested a hemispherical-nose cylindrical afterbody model at Mach number of 0.8 to assess a CAT method for axisymmetrical flow. The emphasis in that work was on the experimental method, reconstruction of the holograms, identification and digitization of the fringe pattern, and a Fourier-transform algorithm to obtain density from the fringe data.

This paper presents the analysis of the complete flow field and compares the results with theoretical calculations to assess the usefulness of this CAT method.

EXPERIMENTAL METHOD

Interferometer

The holographic interferometer is an off-axis, two-beam system. It was specially constructed in 1981 for permanent installation in the 2- by 2-Foot Transonic Wind Tunnel at Ames Research Center. The interferometer uses a pulsed Nd:yag laser to provide a 532-nm output. It was modified by enclosing the object beam in a cloth bellows for the purpose of reducing room air currents, which produced noisy fringes, thereby yielding poorer data. The reference beam was enclosed in a concrete trench. A complete description of the interferometer is given by Craig et al. [10].

Model

The model was a stainless steel hemisphere cylinder, 5.08 cm in diameter and 35.56 cm long. The model was mounted on the tunnel sting support and set to within 0.01° of the centerline of the test section in order to obtain axisymmetric flow. With axisymmetric flow, the density field about the model axis is symmetrical and only one hologram taken normal to the flow is necessary to define the flow.

Holographic Method

Dual-plate interferometry [20] was used to record the holograms. Several reference holograms were taken at zero velocity and several object holograms were taken at the test velocity. From these, at least one set having sufficient fringe contrast, brightness, and sharpness was obtained. The holograms were reconstructed into infinite-fringe interferograms (Fig. 1). In interpreting the interferograms, zero was assigned to the large, bright fringe either in the free stream or in the area well ahead of the model. All subsequent bright fringes were assigned the numbers 1, 2, 3, ..., consecutively. The semiautomatic method of Becker and Meier [21], which relies on an image processor and a minicomputer, was used to digitize the fringes on planes normal to the model axis (Fig. 2a). Van Houten's [22] Fourier-transform method was used to obtain the density by inverting an integral equation relating the index of refraction (hence the density) to the fringe shifts. The method requires equally spaced views of the model over an arc of 180° . According to Sweeney [23], the accuracy increases with more views but so does the computer time. It was decided that 72 views would be a good compromise. (Remember that for axisymmetric flow, only one view is needed to define the flow. This view was repeated 72 times in the Fourier method.)

RESULTS

Figure 1 shows a typical interferogram used for data reduction. Examination of the fringe pattern shows some asymmetry in the flow; it was typical of many obtained at this test condition. The major density changes occurred within a radius of 2 model diameters from the model nose tip. Therefore, the fringes were digitized on 13 planes in this region. The planes were spaced equally one-quarter model diameter apart and were normal to the model axis, as shown in Fig. 2b. Since the model was set for axisymmetric flow, the fringe data were averaged over the upper and lower half of the interferogram for inversion purposes. The apparent asymmetry was due to noise caused by a combination of laser instabilities, reconstruction sensitivity, wind-tunnel vibration, flow angularities, beam wandering, and unsteady shock waves on the model.

The most important noise source was the laser beam wandering. This wandering occurs over a period of several minutes or longer. For the worst case, the beam can move so much that it will miss half of the hologram and make the hologram unusable. Since it takes the tunnel several minutes to reach test condition, the degree of beam wandering within this time period will determine the degree of noise. Some noise can be seen in the region ahead of the model and is exhibited by broad random fringes (Fig. 1). The order of the noise is one fringe and it exists even for ambient flow. This means that the zero fringe, required for accurate results, cannot be determined to within a resolution of one fringe. To resolve this problem, this first inversion plane has to cross a point where the density is known. In this experiment, the known density was at the model nose-tip. This density is the isentropic density at the stagnation condition.

The fringe distribution at the nose-tip plane is shown in Fig. 3. By inverting this fringe distribution and matching the density at the nose tip with the known density, the zero fringe was found. This was done by an iterative technique and was accomplished in two or three iterations. Once the zero fringe was found from the stagnation-point solution, fringes on the entire interferogram were identified. (It should be noted that for a model for which the stagnation point is not easily identified, a known density at some point on the model could be used to determine the zero fringe.)

The inversion process in the region ahead of the nose was straightforward. Behind the nose, fictitious fringes were added in the region where the model blocks the beam because the inversion theory requires continuous data over the entire plane. The inversion code was written with a spline curve-fitting routine to fill in the fictitious fringe data. According to Zien et al. [8], the density solution was not affected by the fictitious fringe distribution for axisymmetric flow. This assumption was checked by assuming three radically different fictitious fringe distributions. The fictitious data from the spline method are plotted in Fig. 4a. The other two curves were chosen to be radically different from the spline curve. The resulting density distributions are shown in Fig. 4b. The densities in the region not blocked by the model were not affected by the distribution of fictitious fringes assumed in the shadow of the model.

Comparisons of the density data with theoretical results are shown in Figs. 5a through 5i. Two computations, those of Coakley [24] and Pulliam [25], were used to assess the accuracy of the data. Both methods solved the steady, inviscid Euler equations. Pulliam's method can handle three-dimensional flows and was used in anticipation of non-axisymmetric cases. Coakley's method can handle only axisymmetric flows; however, it needs only to solve the flow on one plane so, for

equivalent computer time, the mesh size can be smaller and the solution more accurate. Coakley's mesh size was set to be nearly twice as dense as that of Pulliam's.

The comparisons of the experimental and theoretical results in the region ahead of the model are presented in Fig. 5a to 5d; as shown in those figures, the experimental data are within 1% of the theoretical results. Note that there was some scatter in Pulliam's results, a result of the coarse mesh he used. Referring back to Fig. 1, the signal generated in the region ahead of the model was about four fringes, as characterized by the four nearly elliptically shaped fringe patterns. Becker's automatic method digitized the line segment on each bright fringe and used a spline fit to form a smooth curve through the data points. A maximum of 512 pixels or points to curve fit are available in the system. As the results show, very good accuracy was obtained at a signal of four fringes and a noise of one about one fringe. However, at lower signal levels, the accuracy should deteriorate. Lower signals will occur at reduced Mach and Reynolds numbers (based on lower tunnel pressures), and in regions of low density gradients.

An attempt was made to provide more fringe data by reconstructing the interferogram into the finite-fringe mode, as shown in Fig. 6. By superimposing a set of parallel "wedge" fringes on the fringe pattern, more fringe data points were obtained. This method in effect provided an interpolation between the fringes. More parallel fringes can be obtained by increasing the angle between the holograms during reconstruction. At some point, adjacent fringes will tend to merge because of the noise. The interferogram shown in Fig. 6 can probably hold twice as many fringes before merging occurs. The noise can be seen by the degree of waviness of a fringe from a straight line. Without noise, the fringes in the free stream would be straight lines. The noise was found to vary by as much as a fringe. Digitizing the finite-fringe data was a tedious process because the automated scheme was not designed for that purpose. The results of this method did not seem to improve the fringe data over those of the other method and it was subsequently dropped.

Comparison of the experimental data and theoretical results at the nose-tip plane is given in Fig. 5e; the agreement was excellent (within 1%). At the nose tip, or stagnation point, Pulliam's result was 2% low because of the coarse mesh he used. Note the agreement with Coakley's result and remember that the solution was normalized to the isentropic stagnation-point density.

Figures 5 present the comparisons on the hemisphere-nose ($Z/R = 0.5$, Fig. 5f; and 1.0 , Fig. 5g) and just downstream of the hemisphere-nose ($Z/R = 1.5$, Fig. 5h). The agreement between experiment and theory was poor in a region within

2 nose radii of the model. This poor agreement was due to a system of unsteady weak shocks and local flow separation which could not be predicted by a steady, inviscid theory. The shocks, which appeared as wrinkles on the fringes, were very difficult to see and were almost masked by noise, which also caused wrinkled fringes.

In order to see the shocks better, a shadowgraph was reconstructed from the hologram (Fig. 7). The shocks and the flow separation can now be readily seen. A lambda shock was centered at about $Z/R = 1.3$ and the shock on the upper half of the model seems stronger. The boundary-layer separation started at about $Z/R = 0.8$. These results were also observed by Hsieh [26] at Mach numbers of 0.7 to 0.9. Coakley and Pulliam predicted single shock waves located at distances of 1.3 and 1.2, respectively. The flow was observed during the experiment by operating the interferometer as a shadowgraph at 10 to 20 pulses per second. The flow was seen to be unsteady and the shocks oscillated and varied in strength with time. The data in Figs. 5f-5g showed that beyond 2 nose radii, or beyond the influence of the shocks, the agreement between experiment and theory was again within 1%.

Figure 5i shows a typical density profile in the cylindrical portion of the model. The flow in this region approaches uniform free-stream density. The data approached the free-stream values faster than the predictions. This is probably a result of the deterioration of the experimental accuracy. The signal-to-noise ratio in the region is about 1. The maximum deviation between the data and the predictions was about 2%.

CONCLUDING REMARKS

This computer-aided tomography experiment, conducted in a large wind tunnel using a state-of-the-art laser holographic system and a recently developed semiautomated digitizing system, demonstrated the feasibility of using tomographic methods to make accurate density measurements. Three changes are indicated that would improve the quality of the holograms, make the reconstruction easier, and speed up the data process. First, a laser with improved stability would reduce the beam wandering and noise and improve accuracy. Second, the use of newly developing thermoplastic recording devices would permit faster and more accurate reconstructions. And third, a positive method for reconstructing infinite-fringe interferograms would also improve accuracy.

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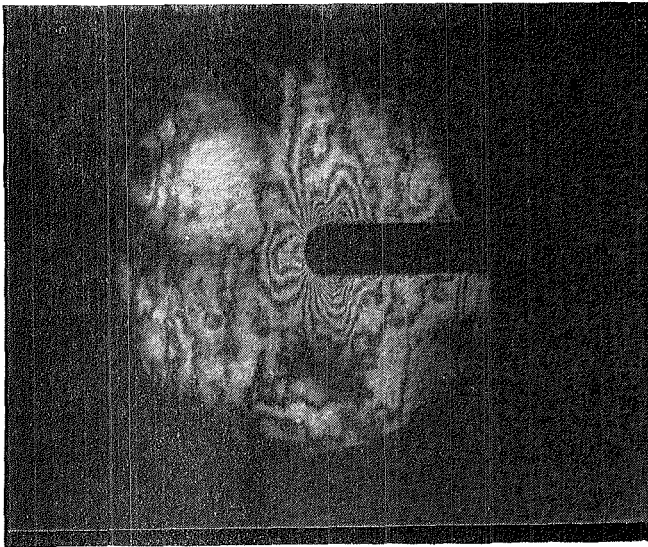
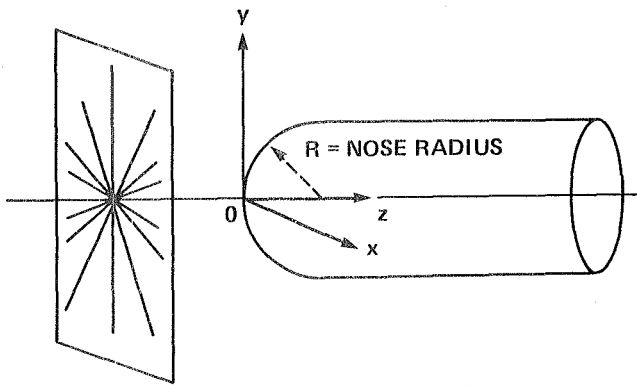
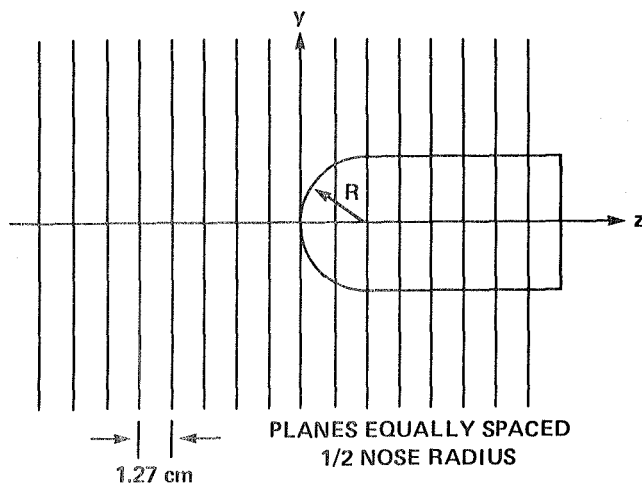


Fig. 1 Typical infinite-fringe interferogram.



a) Typical plane for digitization; plane is normal to model axis and radial lines are lines on which data are processed.



b) 13 planes used for data reduction covering $Z/R = \pm 3$.

Fig. 2 Planes used for digitization.

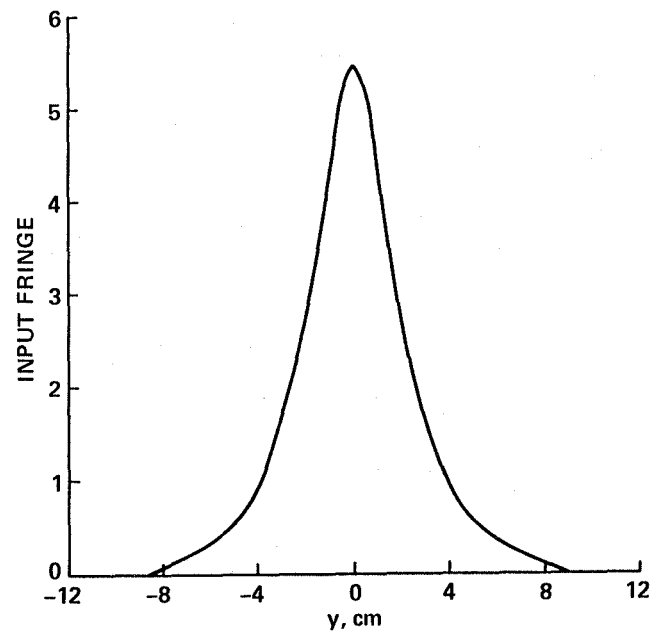
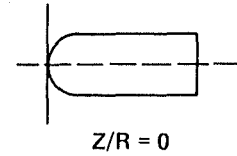


Fig. 3 Fringe distribution on the nose-tip plane: $Z/R = 0$.

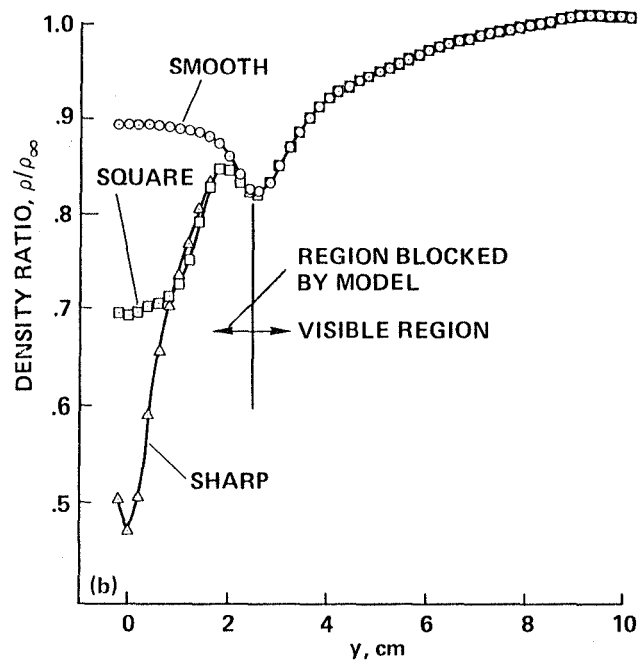
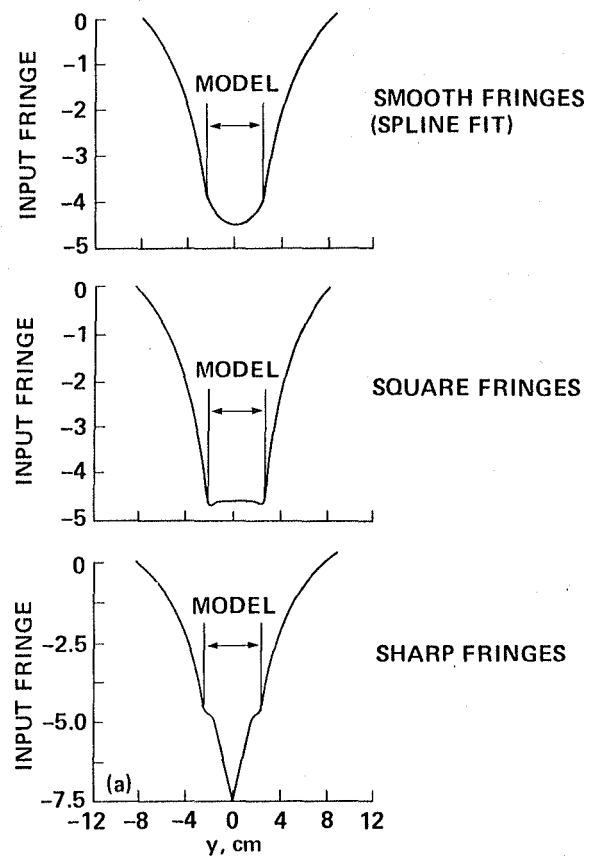


Fig. 4 Effect of fictitious fringes in the region of the model. a) Fictitious fringe distributions; b) density ratio.

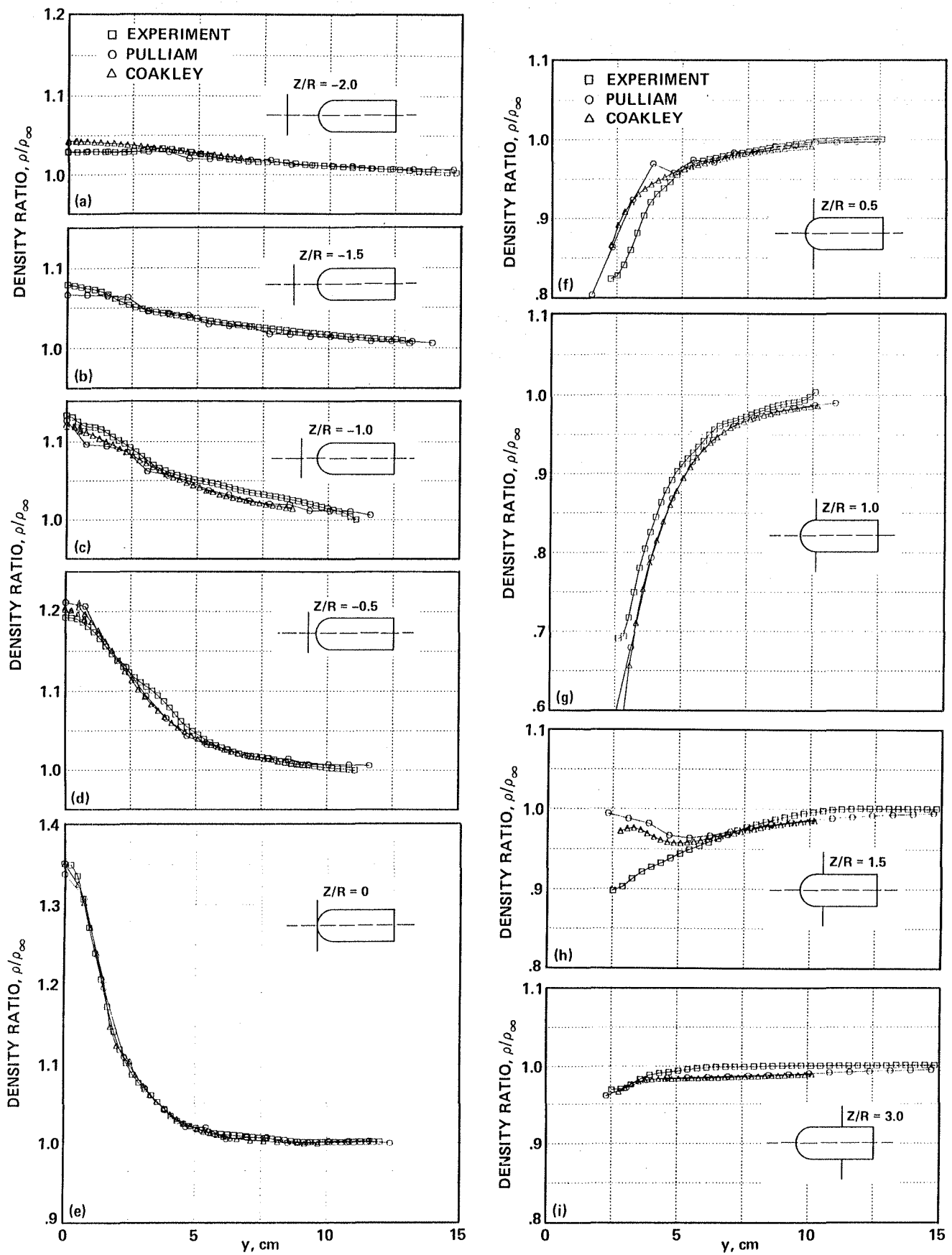


Fig. 5 Comparison of experimental and theoretical data at nine planes. a) $Z/R = -2.0$; b) $Z/R = -1.5$; c) $Z/R = -1.0$; d) $Z/R = -0.5$; e) $Z/R = 0$; f) $Z/R = 0.5$; g) $Z/R = 1.0$; h) $Z/R = 1.5$; i) $Z/R = 3.0$.

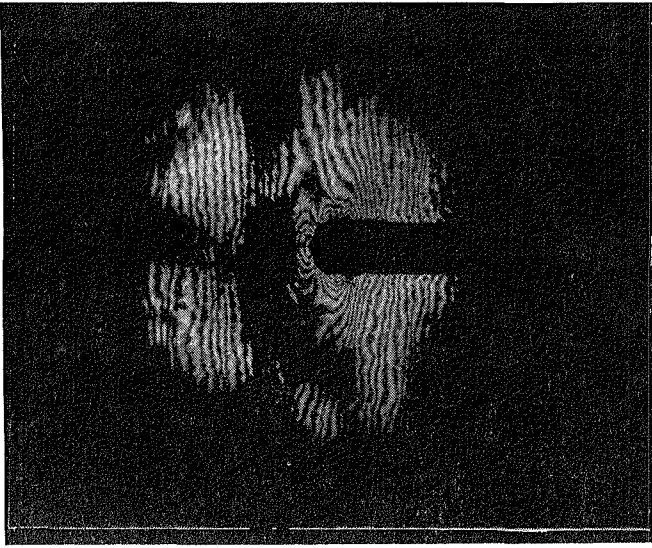


Fig. 6 A typical finite-fringe interferogram.

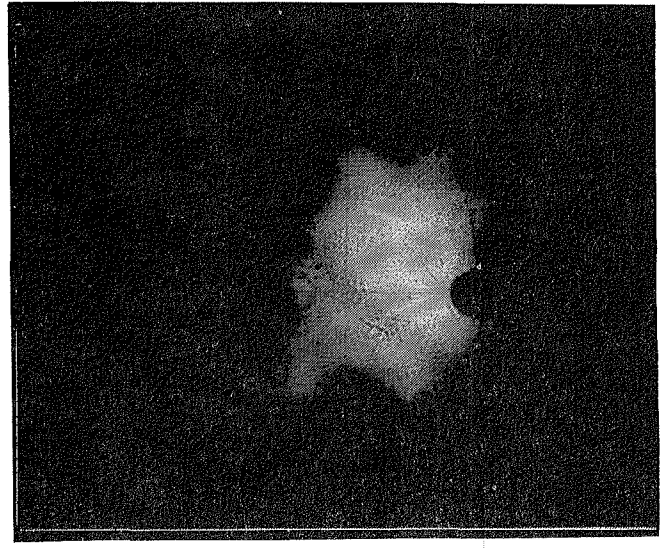


Fig. 7 Shadowgraph showing shock waves.

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